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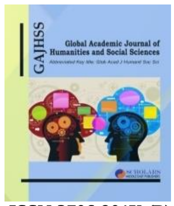

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Review Article

Transforming Smallholder Agriculture Amid Water Scarcity: A Systematic Review of the Socio-Economic Benefits of Micro-Irrigation Technologies

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Abstract: The review focuses on the socio-economic benefits of micro-irrigation technologies (MITs) for smallholder farmers, highlighting their potential to transform agricultural practices and enhance sustainability. The review synthesizes empirical evidence from Africa and Asia, providing a comprehensive overview of how MITs can positively impact smallholder agriculture. Findings reveal that the adoption of MITs leads to significant improvements in agricultural productivity and enhanced water use efficiency, which contributes to reduced operational costs. Additionally, the financial resilience of smallholder farmers improves as they become better equipped to navigate market fluctuations and economic challenges. These benefits not only bolster individual livelihoods but also promote broader economic stability within rural communities. The review recommends several strategies for effective implementation. These include promoting awareness and adoption among farmers, enhancing access to finance, building technical capacity, supporting research and innovation, enacting supportive policies, and establishing models to assess the economic viability of MITs.

Keywords: Micro-irrigation technologies, drip irrigation, sprinkler irrigation, smallholder farmers, socio-economic benefits of micro-irrigation technologies.

1.0 INTRODUCTION

Agricultural production is increasingly threatened by the dual challenges of global water stress and climate change. As freshwater resources dwindle and climate variability intensifies, agriculture, especially in arid and semi-arid regions, faces significant risks to its sustainability and productivity (Agbenyo *et al.*, 2022) .The Food and Agriculture Organization (FAO) warns that climate change will exacerbate water scarcity, impacting food production systems worldwide (Food and Agriculture Organization 2020). This situation is particularly critical for smallholder agriculture, which contributes up to 80% of global food production and is highly dependent on reliable water availability (Assefa, Ayalew, and Mohammed 2022).

Micro-irrigation technologies (MITs), such as drip and sprinkler systems, have emerged as essential solutions to these challenges (Martínez-Arteaga *et al.*, 2023; Sarkar and Hanamashetti 2002). These technologies facilitate precise water management, allowing for the conservation of scarce resources while simultaneously enhancing crop yields and ensuring food security (Han *et al.*, 2023a; J. Wang *et al.*, 2022a). With irrigation accounting for approximately 40% of global food production, the adoption of MITs is vital for mitigating the adverse effects of climate change on agriculture and meeting the growing demands of a rising global population (Mattoussi, Mattoussi, and Larnaout 2023).

Despite efforts to promote the adoption of micro-irrigation technologies among smallholder farmers, there remains a gap in understanding their actual contributions to socio-economic development of small holder farmers (Narpat Singh and Dangi 2022; SAXENA *et al*., 2022). While interest in MIT adoption has grown, comprehensive reviews assessing their social and economic impacts are lacking. Therefore, this review aimed to explore the benefits of MITs in transforming agricultural practices and improving the livelihoods of smallholder farmers. By synthesizing existing literature and empirical evidence, the review seeks to provide insights into how MITs enhance crop yields, improve water use efficiency, yield and economic benefits while addressing social implications for smallholder farmers.

The central research question guiding this review was to assess the social and economic benefits of MITs on smallholder agriculture, and how do they contribute to the transformation of farming practices and livelihoods. Through this inquiry, the review aspires to inform policymakers, practitioners, and researchers about the significance of adopting MITs and support initiatives aimed at their effective implementation in smallholder agriculture.

2.0 METHODOLOGY

2.1 Study design

A systematic review of existing literature was conducted to collect evidence of the benefits of MITs on agriculture production. Production indicators hereby referred as outcomes variables were income levels, income and financial resilience, farm operation cost, crop yields, food security, water use efficiency, and livelihood improvements, climate change resilience as well as environmental sustainability. When necessary, secondary effects emanated from those variables were also collected as benefits of MITs. The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) model was used to guide the selection of published literature from journals and databases.

2.2 Literature search

A search for literature was focused on the published research articles, book chapters, and conference proceedings on the socio-economic benefits of micro-irrigation technologies. Multiple keywords, synonyms, related terms, and variations were combined during the identification phase using Boolean operators "OR" and/or "AND": "micro-irrigation technologies", "micro irrigation technology AND economic benefits", "micro irrigation technology AND social benefits", "profitability AND drip irrigation OR precision irrigation", "socioeconomic benefits AND micro-irrigation technologies", "sprinkler irrigation", "benefits of micro irrigation technologies" and "micro irrigation system". The search for peer-reviewed articles was conducted in three databases, i.e. Scopus, Research4Life, and Google Scholar, focusing on papers published from year 2013 to 2023 as it is the decade of irrigation technology advance.

2.3 Inclusion and exclusion criteria

The systematic review included the studies that focused on, articles or publications in English language, articles from developing countries in Africa and Asia and publications from 2013 to 2023 as major advancements in irrigation technology occurred during this decade. Other criterion included articles that focused on MITs and studies that related MITs with social and economic benefits to smallholder farmers.

Articles that were not related to any of the inclusion criteria were excluded at different stages of screening. Each study was independently assessed by two reviewers to ensure objectivity and reduce bias.

2.4 Data synthesis

The following information was extracted from each article/study: Demographic characteristics, socio-economic status, household information, types of micro-irrigation technologies used, scale, and duration of their use. Also, economic variables like crop yields, income, and costs, along with social variables such as livelihood outcomes and access to services, were collected. In addition, environmental variables, including water use efficiency, and impact on soil health and biodiversity, were considered, as well as information on funding and support mechanisms for MIT adoption. A qualitative approach was used to analyse socio-economic benefits of MITs (Creswell 2014; Campbell *et al*., 2024).

3.0 RESULTS AND DISCUSSION

3.1 Literature search and selection

The detailed search and assessment results of literature is shown in Figure 1. Initial search querry for MITs in relation to agriculture productivity resulted to 534 studies. One hundred and ninety nine (196) were discarded due to dublicates and 132 more were discarded due to irrelevancy after screening the titles and abstract. Additional 22 articles were discarded since they could not be retrieved. Finally, 184 were found aligible for the review as shown in Fugure 1.

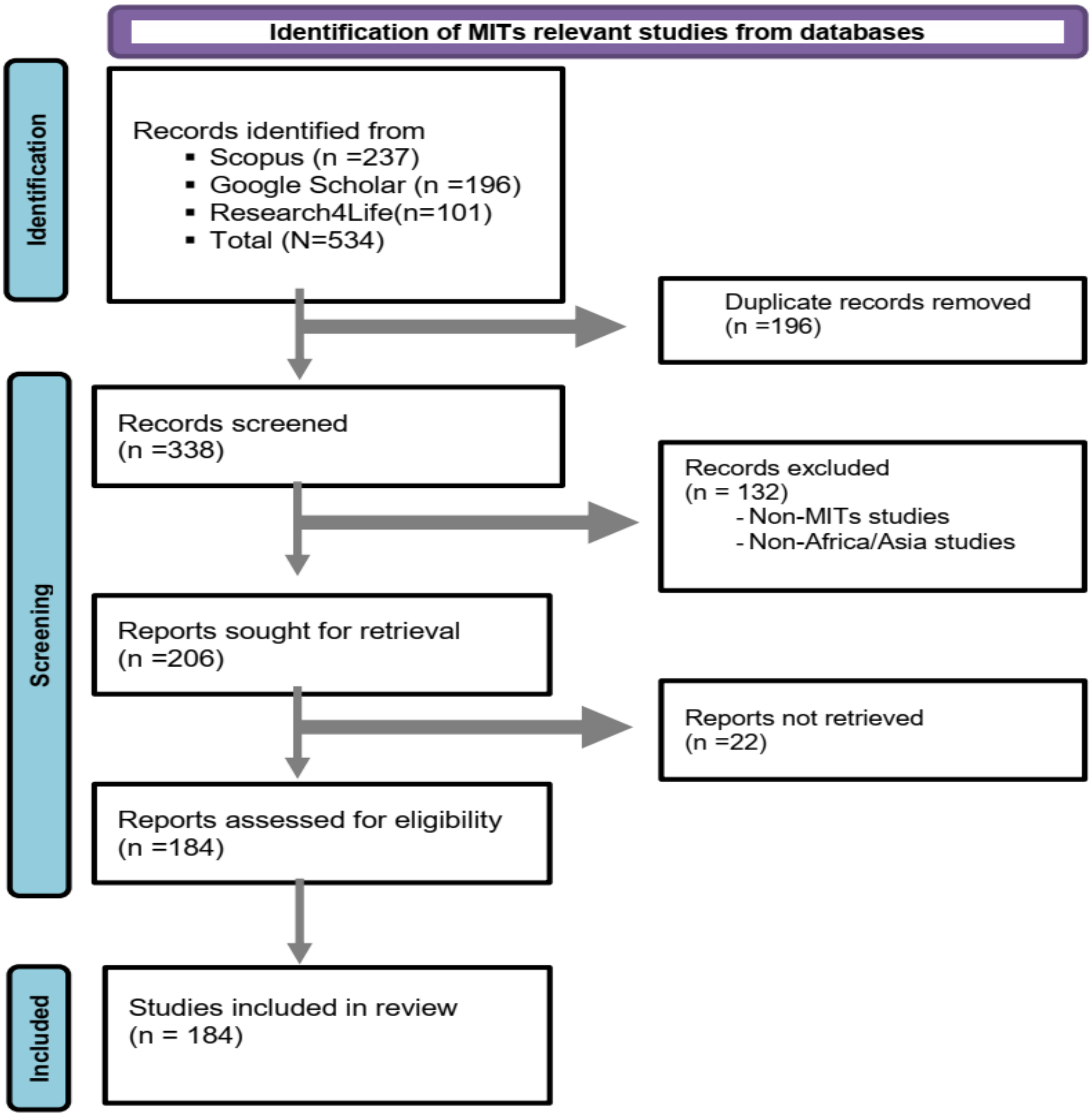

Figure 1: PRISMA Model for identification, screening and selection of studies for systematic review of the benefits of MITs in agricultural production. Adapted from (Moher *et al.*, 2015)

3.2 Types of micro-irrigation technologies

The present study revealed various types of MITs, which are drip irrigation, sprinkler irrigation, micro-sprinkler irrigation, and subsurface drip irrigation (Andrezejewski 2014; Ashoka, Kadasiddappa, and Sanjey 2015; Patle, Kumar, and Khanna 2020a).

Drip irrigation was preferred since it delivers water directly to the base of each plant through a network of tubes or pipes with emitters (Sarkar and Hanamashetti 2002). Sprinkler systems distribute water over the crop area through overhead sprinklers or nozzles (Abd El-Hafez, Mahmoud, and El-Bably 2020). This method mimics natural rainfall and is suitable for a wide range of crops. However, it can be less water-efficient than drip irrigation due to greater evaporation (Tang *et al*., 2022; El-Wahed *et al*., 2015a; Shen and Yi 2015). Similar to traditional sprinkler systems but with smaller sprinklers, micro-sprinkler irrigation delivers water more precisely to the root zone of plants. This method is suitable for row crops and orchards (Abd El-Hafez, Mahmoud, and El-Bably 2020; Ferreira *et al*., 2016a; Yue *et al*., 2023; Kakhandaki, Padmakumari, and Patil 2013; Shen and Yi 2015; Li 2018). Subsurface drip irrigation (SDI) systems deliver water directly to the root zone of plants buried beneath the soil surface (Abd El-Hafez, Mahmoud, and El-Bably 2020; Tang *et al*., 2022; Kakhandaki, Padmakumari, and Patil 2013; Shinde 2013; El-Wahed *et al*., 2015a). This method minimizes water loss due to evaporation and surface runoff, making it particularly efficient for water-saving irrigation (Camp 1998; Zaccaria *et al*., 2017a; Solano *et al*., 2022a). In contrast to SDI, surface drip irrigation systems place drip lines or emitters on the soil surface. This method is suitable for crops planted in rows and provides flexibility in irrigation scheduling (Aydinsakir *et al*., 2021; Solano *et al*., 2022a; Al-Ghobari and Dewidar 2018a).

3.3 Economic Benefits of Micro Irrigation Technologies

3.3.1 Increased income and profitability

The profitability of micro-irrigation technologies (MITs) has been a subject of extensive debate among scholars, who have emphasized the economic advantages of modern irrigation systems, focusing on the potential to boost the financial viability of farming operations (Bhatti *et al*., 2022a; Osewe, Liu, and Njagi 2020). The adoption of micro-irrigation technologies has been consistently associated with increased income and profitability among smallholder farmers, as evidenced by various studies in the agricultural research literature (Matović *et al*., 2016; Asante 2013). MIT enables farmers to achieve higher crop yields and improved crop quality through precise water and nutrient management, ultimately leading to enhanced marketability and profitability of their produce (H. P. Singh and Singh 2020a; Rao, Anitha, and Rao 2021a; Ali *et al*., 2020a). For example, research by (Ali *et al*., 2020a; Rao, Anitha, and Rao 2021a) demonstrated that the adoption of drip irrigation systems resulted in a significant increase in crop yields and net returns compared to conventional irrigation methods in various cropping systems, and the increase in productivity translates into higher revenues for farmers, thereby augmenting their overall income levels.

Additionally, (Adebayo *et al*., 2018a; de Bont and Veldwisch 2020) demonstrate that the economic benefits of adopting micro-irrigation are manifested in enhanced profitability. Similarly, (Osewe, Liu, and Njagi 2020; Bojago and Abrham 2023) highlighted the advantageous economic trajectory, elucidating how micro-irrigation technologies lead to higher yields, lower production costs, and increased profitability, offering a promising route for bolstering smallholder farmers' financial prospects.

Moreover, MITs contribute to cost savings and efficiency gains in agricultural production, further bolstering profitability for farmers (I. Hussain and Hanjra 2004) (A. Hussain *et al*., 2022a; Zou *et al*., 2013a)optimizing water use and minimizing waste, the MIT reduces irrigation costs and water-related expenses, resulting in significant economic savings for farmers (Zou *et al*., 2013a). MIT also leads to reductions in labor costs associated with irrigation activities, as automated or semi-automated systems require less manual intervention and maintenance than traditional irrigation methods (Nkya, Mbowe, and Makoi 2015a; Grant *et al*., 2020). As noted by (Hornum, Bolwig, and Trærup 2023a; Bhatti *et al*., 2022a), Drip irrigation has the potential to improve smallholder farmers' economic welfare by increasing farm yield and income (Matović *et al*., 2016; H. P. Singh and Singh 2020a). However, increased income can be used in various ways, such as asset building, child education, and loan repayment, all of which contribute to improving the livelihoods of farming communities (Engdasew Feleke, Engdawork Assefa, and Tesfaye Zeleke 2019; Sherpa, Patle, and Rao 2021a) These cost-saving benefits contribute to improved profitability and financial viability of farming operations, particularly for resource-constrained smallholder farmers.

Furthermore, the adoption of MIT facilitates the diversification of crop production and value chain integration, opening up new market opportunities and avenues for revenue generation (SILVA *et al*., 2022; Moursy *et al*., 2023). Farmers using MIT are often able to cultivate high-value specialty crops or engage in niche markets that command premium prices, thereby increasing their overall profitability (Zou *et al*., 2013a; Sissoko, Synnevag, and Aune 2022). The improved crop quality resulting from MIT adoption enhances marketability and consumer demand for farmers' produce, leading to higher sales volumes and better price realization in the marketplace (Rajput and Patel 2021; Bhamoriya 2017; Lynch 1999).

3.3.2 Increased Crop Yield

Studies have demonstrated that MITs contribute to improved crop growth and development by maintaining optimal soil moisture levels and nutrient availability throughout the growing season (Yang *et al*., 2023). This ensures that crops receive the necessary water and nutrients required for optimal physiological functioning, leading to enhanced photosynthesis, biomass accumulation, and ultimately increased yields (Yang *et al*., 2023; Rajwade *et al*., 2018). (Adebayo *et al*., 2018a; de Bont and Veldwisch 2020) demonstrated that the economic benefits of adopting micro-irrigation are manifested in increased crop yields. Similarly, (Bojago and Abrham 2023; Osewe, Liu, and Njagi 2020) highlighted the advantageous economic trajectory, expounding how micro-irrigation technologies lead to higher yields.

Moreover, the precision irrigation capabilities of the MIT allow for targeted water application based on crop water requirements, soil characteristics, and climatic conditions, thereby minimizing water waste and maximizing crop productivity (Mačkić *et al*., 2023; J. Wang *et al*., 2022b). By delivering water directly to the root zone where it is most needed, MIT reduces water stress on crops, particularly during critical growth stages such as flowering and fruit development, resulting in higher yields and improved crop quality (Han *et al*., 2023b; Solano *et al*., 2022b; Adebayo *et al*., 2018b).

Furthermore, MIT facilitates the adoption of water-saving agricultural practices such as deficit irrigation and regulated deficit irrigation, which strategically manipulate water availability to crops to optimize yield performance while conserving water resources (Chomsang *et al*., 2021; Dawit, Dinka, and Leta 2020; Xia *et al*., 2021). Through precise control over irrigation scheduling and application rates, farmers can tailor water management strategies to suit specific crop requirements and environmental conditions, thereby maximizing yields while minimizing water consumption (X. Wang, Lu, and Yang 2021; Shatkovskyi, Hulenko, and Kalilei 2022; Jain, Bhatt, and Singh 2022; Kumar 2016; Dewedar *et al*., 2021).

3.3.3 Savings and financial resilience

The application of micro-irrigation technologies fosters household savings capacity and financial resilience among smallholder farmers, as evidenced by numerous studies in the agricultural research literature (Chidavaenzi, Mazenda, and Ndlovu 2021a). MIT enables farmers to achieve cost savings and efficiency gains in agricultural production, particularly through the optimization of water use and reduction in input costs (Zou *et al*., 2013b; Nkya, Mbowe, and Makoi 2015b). By minimizing water wastage and maximizing water efficiency, the MITs lead to reductions in irrigation costs, water-related expenses, and labor costs associated with irrigation activities (Mangisoni 2006a; Ferreira *et al*., 2016b). These cost-saving benefits translate into increased disposable income for farmers, which can be allocated to savings or investments in other income-generating activities (Adebayo *et al*., 2018b).

MITs provide farmers with greater control over water management and mitigate the risks associated with climate variability and water scarcity (Patle, Kumar, and Khanna 2020a; Birkenholtz 2017). By ensuring a reliable water supply for crop production, the MITs reduce the vulnerability of farmers to crop failures and income fluctuations caused by droughts or erratic rainfall patterns (Kulyakwave, Wen, and Shiwei 2023; Hornum, Bolwig, and Trærup 2023b; Yadav A *et al*., 2022). This stability in agricultural income enables households to maintain financial stability and meet their basic needs, even during challenging times, thereby enhancing overall financial resilience (Chidavaenzi, Mazenda, and Ndlovu 2021a).

Moreover, the economic benefits generated by MIT, such as increased savings capacity and financial stability, enable households to access credit and financial services, further strengthening their financial resilience (Priyan and Panchal 2018a)With improved creditworthiness and access to financial resources, farmers can invest in productivity-enhancing inputs, expand their agricultural operations, or diversify their income sources, thereby reducing their reliance on agriculture as the sole source of livelihood and enhancing their overall resilience to economic shocks (Srivastava *et al*., 2003; Ali *et al*., 2020b; Bhatti *et al*., 2022b).

3.3.4 Efficient water use and savings

Efficient water use is a key advantage of micro-irrigation technologies and significantly contributes to their economic and environmental benefits (Chunyao Huang, Lu, and Du 2020). The research literature consistently demonstrates the effectiveness of MIT in optimizing water usage and minimizing water wastage, thereby enhancing agricultural productivity while conserving scarce water resources (Cremades *et al*., 2016; Vaddevolu *et al.*, 2021a).

The MITs system, such as drip irrigation and sprinkler systems, deliver water directly to the root zone of crops in a controlled and precise manner, minimizing losses due to evaporation, runoff, and deep percolation (Nasib Singh and Singh Malik 2018; Vaddevolu *et al*., 2021b; Yue *et al*., 2023) This targeted water application ensures that crops receive the right amount of water at the right time, maximizing water use efficiency and reducing overall water consumption (Deng *et al*., 2021; Xiuling *et al*., 2023; Zou *et al*., 2013b)

Furthermore, MIT allows for the customization of irrigation schedules and application rates based on specific crop water requirements, soil moisture levels, and environmental conditions (Chathuranika *et al*., 2022; Y. Wang *et al*., 2021; Mačkić *et al*., 2023). Through the use of advanced technologies such as soil moisture sensors and automated irrigation controllers, farmers can precisely manage water delivery, optimize irrigation scheduling, and minimize crop overwatering or underwatering (Chikushi, Villavicencio Floriani, and Toyota 1997; Patle, Kumar, and Khanna 2020a; Dewedar *et al*., 2021; Dwijendra *et al*., 2022; Yang *et al*., 2023).

The efficient water use facilitated by MIT not only improves crop yields and quality but also contributes to water conservation and environmental sustainability (Ashoka, Kadasiddappa, and Sanjey 2015; C. Sowthanya & T. R. Shanmugam 2019; El-Wahed *et al*., 2015b). By reducing water losses and minimizing the need for excessive pumping, MIT helps to conserve limited water resources, particularly in water-stressed areas

(Ho, Hoang, and Wilson 2022; H. P. Singh and Singh 2020b; Kumar 2016; Al-Ghobari and Dewidar 2018b). This sustainable water management approach supports long-term agricultural productivity and resilience, ensuring the availability of water for future generations (Sachan and Patel 2023; Van der Kooij *et al*., 2013; Viswanathan, Bahinipati, and Mohanty 2022; Sidhu *et al*., 2021; Yadav A *et al*., 2022).

3.3.5 Reduced Farm Operational Costs

The adoption of micro-irrigation technologies is associated with reduced operational costs for agricultural production, as evidenced by research findings in the agricultural literature (A. Hussain *et al*., 2022b; Zou *et al*., 2013b). The MITs, such as drip irrigation and sprinkler systems, offer efficiency gains and cost-saving benefits compared to traditional irrigation methods, leading to improved economic viability and sustainability for farmers (Nkya, Mbowe, and Makoi 2015b; A. Hussain *et al*., 2022b).

One of the primary mechanisms through which MIT reduces operational costs is by minimizing water waste and optimizing water use efficiency (Cremades *et al*., 2016; S. Singh *et al*., 2013). MIT delivers water directly to the root zone of crops in a controlled and precise manner, thereby minimizing losses due to evaporation, runoff, and deep percolation (Deng *et al*., 2021; Xiuling *et al*., 2023). This targeted water application ensures that crops receive the right amount of water at the right time, reducing overall water consumption and associated costs for irrigation (Chathuranika *et al*., 2022; Y. Wang *et al*., 2021; ZHAI *et al*., 2021)

Moreover, MITs enable farmers to achieve labor savings and efficiency gains in irrigation management (Grant *et al*., 2022). Compared to labor-intensive methods such as flood irrigation, the MITs require less manual labor for installation, operation, and maintenance (Mangisoni 2006a). Automated features such as timers, sensors, and controllers facilitate precise water delivery and irrigation scheduling, reducing the need for constant monitoring and manual intervention by farmers (Nejadrezaei *et al*., 2018; Priyan and Panchal 2018b)

Additionally, MITs contribute to energy cost savings associated with irrigation pumping (Gao *et al*., 2018a). By minimizing water losses and optimizing water distribution, MITs reduce the energy required to pump water from water sources to agricultural fields (Mangisoni 2006a). This results in reduced fuel or electricity consumption for irrigation pumping, leading to cost savings for farmers and enhancing the overall economic efficiency of agricultural production (Namara, Nagar, and Upadhyay 2007; Gorain *et al*., 2020; Reddyj *et al*., 2004).

Furthermore, the adoption of MITs can lead to reductions in input costs related to fertilizers and agrochemicals (Singh Purohit, Gyan Singh Purohit, and Goyal 2017). The precise water and nutrient management provided by MITs minimize leaching and runoff, reducing the need for excess fertilizers and chemicals (Chunyao Huang, Lu, and Du 2020; Chikushi, Villavicencio Floriani, and Toyota 1997). This not only lowers input costs for farmers but also contributes to environmental sustainability by minimizing the negative impacts of agricultural runoff on water quality and ecosystem health (Khalifa W, Gasmi H., and Butt T. 2020; Rao, Anitha, and Rao 2021b; Saha, Purohit, and Bhandari 2000; Johnpaul, Jayakumar, and Sindhu 2021).

3.4 Social Benefits of Micro Irrigation Technologies

3.4.1 Food security

Micro-irrigation technologies play a critical role in enhancing food security and increasing crop yields for farming households in rural farming communities (Gwambene, Liwenga, and Mung'ong'o 2023; Sissoko, Synnevag, and Aune 2022; Abdulsemed Abanega Abdurahman and Ahmed Mohammed Abachebsa 2021). MITs allow farmers to cultivate a diverse range of crops even in regions with limited rainfall (Mangisoni 2006b; Patle, Kumar, and Khanna 2020b; Agbenyo *et al*., 2022). This increased crop diversity contributes to dietary diversity within households, reducing reliance on a single staple crop and improving nutritional intake (Food and Agriculture Organization 2020; Adebayo *et al*., 2018a; Chidavaenzi, Mazenda, and Ndlovu 2021b; Sissoko, Synnevag, and Aune 2022).

Studies have shown that compared with traditional irrigation methods, micro-irrigation systems can increase crop yields by up to 50%, particularly in water-stressed environments (El-Wahed *et al*., 2015a; H. P. Singh and Singh 2020a). Higher yields not only ensure a more reliable food supply for farming households but also create surpluses that can be sold or stored for consumption during lean periods, further strengthening food security (Adebayo *et al*., 2018a; Sissoko, Synnevag, and Aune 2022).

The economic benefits generated by micro-irrigation technologies, such as increased income and improved financial stability, enable smallholder farmers to invest in agricultural inputs, including seeds, fertilizers, and pest control measures, further enhancing crop productivity and food security (Osewe, Liu, and Njagi 2020; Odoh *et al*., 2020; Sissoko, Synnevag, and Aune 2022).

3.4.2 Resilience to climate change

Micro-irrigation technologies contribute to improved resilience to climate variability and extreme weather events, which are increasingly affecting agricultural productivity and food security (Kulyakwave, Wen, and Shiwei 2023; Hornum, Bolwig, and Trærup 2023b; Yadav A *et al*., 2022). By providing farmers with greater control over water management, micro-irrigation technologies help mitigate the impact of droughts and erratic rainfall patterns, allowing for continued crop production even under adverse conditions (Misquitta and Thatte 2018; Bhardwaj *et al*., 2019; Zou *et al*., 2013b). This resilience to climate shocks is essential for safeguarding food security and livelihoods in vulnerable farming communities (Nkya, Mbowe, and Makoi 2015b; Sherpa, Patle, and Rao 2021b; Valliammai *et al*., 2022). Therefore, it is evident that micro-irrigation technologies have improved resilience to climate change. Hence integrating these technologies into agricultural systems can enhance adaptive capacity and mitigate the adverse effects of climate variability and extremes on farming communities.

3.4.3 Livelihood benefits

Several studies have indicated a strong linkage between the application of micro-irrigation systems and livelihood improvement, as proposed by (Akudugu, Millar, and Akuriba 2021) and the literature indicates that small-scale irrigation is a valuable method for alleviating poverty (Bhatti *et al*., 2022a). (Gebre Gidey 2020) performed a qualified analysis of the impact of small-scale irrigation on livelihood improvement and argued that irrigation alleviates poverty both directly and indirectly, where the direct impacts are realized through labor and land intensification effects that eventually translate to improved productivity, employment, and income. Indirectly the impact of micro-irrigation technologies is realized through enhanced welfare, as evidenced by improvements in various indicators of human, social, natural, and technical capital.

Farmers utilizing small-scale irrigation technologies exhibited a notably enhanced livelihood index, reflective of advancements in several key domains, including human capital (Tan *et al*., 2021; Upadhyay, Samad, and Giordano 2005). Improvements in education and health outcomes enhancing living standards and housing quality among smallholder farming households, as well as social capital, manifested through strengthened community cohesion and collaborative water management practices are also identified in the literature (Upadhyay, Samad, and Giordano 2005; Sachan and Patel 2023). Moreover, the adoption of micro-irrigation systems facilitates access to natural capital, contributing to sustainable resource utilization and environmental stewardship (Zaccaria *et al*., 2017b; Chidavaenzi, Mazenda, and Ndlovu 2021a; K. G. Singh 2015).

Micro-irrigation practices are a cornerstone for enhancing rural livelihoods, as consistently highlighted in empirical research. (Bojago and Abrham 2023) reported that small-scale irrigation significantly boosts household livelihood diversification, ultimately increasing the quality of life of rural households. Additionally,(DiGennaro and Kraybill 2015) asserts that micro-irrigation technologies proved superior in advancing various livelihood indices, such as human, social, and technical capital, represented by the acquisition of working tools and transportation assets to improve housing infrastructure. Concurrently, expanded access to health and education services signifies a broader societal benefit, indicative of improved well-being and human development outcomes within rural communities (Sherpa, Patle, and Rao 2021b; Bhatti *et al*., 2022b). By providing a pathway out of poverty, micro-irrigation technologies contribute to the overall well-being and resilience of smallholder farming households (Adeoti 2009; Mangisoni 2006a).

3.4.4 Environmental Sustainability:

MIT promotes environmentally sustainable agricultural practices by reducing water usage, minimizing soil erosion, and conserving natural resources (Khalifa W, Gasmi H., and Butt T. 2020). By adopting MIT, farmers contribute in the preservation of ecosystems and biodiversity, ensuring the long-term viability of agricultural landscapes for future generations (Rao, Anitha, and Rao 2021b). MIT promotes environmental sustainability through water conservation and efficient water management practices (Saha, Purohit, and Bhandari 2000; Cremades *et al*., 2016). By delivering water directly to the root zone of crops in a controlled and precise manner, MIT minimizes water waste and reduces overall water consumption in agriculture (Soman 2021; Bai, Wan, and Kang 2020).

Additionally, the MITs help mitigate the adverse environmental impacts associated with conventional irrigation methods, such as surface flooding and furrow irrigation, which often lead to soil erosion, salinization, and waterlogging (Malchev, Kornov, and Hansmann 2022; Deng *et al*., 2021). The targeted water application of MITs reduces runoff and soil erosion, preserving soil fertility and preventing nutrient leaching into water bodies (Xia *et al*., 2021; X. Wang, Lu, and Yang 2021; Rajwade *et al*., 2018).

Furthermore, the MITs facilitate the adoption of water-saving agricultural practices, such as deficit irrigation and regulated deficit irrigation, which optimize water use efficiency while maintaining crop productivity (Chunyao Huang, Lu, and Du 2020; Cremades *et al*., 2016). By strategically managing water resources and minimizing water stress on crops, MITs contributes to the conservation of freshwater resources and mitigates the risks of water scarcity and drought (Zaccaria *et al*., 2017b; K. G. Singh 2015; Sachan and Patel 2023).

Moreover, the adoption of MITs can reduce energy consumption and greenhouse gas emissions associated with agricultural production (Rao, Anitha, and Rao 2021b). Compared to conventional irrigation methods, the MITs require less energy for pumping and distribution of water, resulting in a lower carbon footprint and reduced reliance on fossil fuels (Gao *et al*., 2018b; Mangisoni 2006a). This promotes energy efficiency and environmental sustainability in agriculture, contributing to climate change mitigation efforts (Ho, Hoang, and Wilson 2022; Suryavanshi, Buttar, and Brar 2015; Patle, Kumar, and Khanna 2020a).

4.0 CONCLUSION AND RECOMMENDATIONS

Micro-irrigation technologies play a pivotal role in transforming smallholder agricultural production by offering many socio-economic benefits. Through efficient water use, reduced operational costs, increased income, and enhanced financial resilience, the MITs contribute to the economic viability and sustainability of farming operations. The adoption of MITs leads to higher crop yields, improved crop quality, and cost savings, ultimately resulting in increased profitability for smallholder farmers. Additionally, the MITs facilitate water conservation, labor efficiency, and input cost reductions, further enhancing the economic efficiency of agricultural production. These socio-economic impacts not only improve the livelihoods of farming households but also contribute to rural development and poverty alleviation.

To enhance the adoption and impact of micro-irrigation technologies (MITs) in smallholder agricultural production, several recommendations have been proposed. First, efforts should focus on promoting MIT adoption among smallholder farmers through various means, such as training programs, financial incentives, and technical support. Access to affordable financing mechanisms tailored to support investments in micro-irrigation infrastructure is essential for facilitating adoption. Additionally, building the technical capacity of farmers in MIT design, installation, operation, and maintenance is crucial for successful adoption and sustainable use.

Research and innovation play a vital role in developing cost-effective and context-specific MIT solutions that address the needs of smallholder farmers. Collaboration between academia, government agencies, and industry stakeholders is necessary to drive technological advancements and address emerging challenges. Supportive policies and regulations that incentivize MIT adoption and promote sustainable water management practices are imperative. Long-term monitoring and evaluation of MIT adoption programs are essential for assessing socioeconomic impacts, identifying challenges, and informing evidence-based decision-making.

By implementing these recommendations, stakeholders can maximize the socio-economic benefits of MIT adoption and catalyze positive transformation in smallholder agricultural production. This will contribute to food security, poverty reduction, and sustainable rural development, ultimately improving the livelihoods of farming communities.

Limitations

The evidence included in this review has several limitations. Firstly, there is heterogeneity in study designs, methodologies, and outcomes measured, making direct comparisons challenging. Some studies may suffer from selection bias, as they often involve specific regions or communities, limiting the generalizability of findings. Additionally, the quality of the studies varies, with some lacking rigorous methodological approaches. The reliance on self-reported data can introduce recall bias. Finally, the relatively short duration of many studies may not capture the long-term impacts of micro-irrigation technologies on socio-economic outcomes.

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